

TRAPPING OF TRANSURANIUM ELEMENTS BY THE EARTH'S MAGNETIC FIELD

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The search for a transuranium element component of cosmic radiation has been carried out in high altitude balloon experiments by Price, Fleischer, Walker and Fowler. We show that the trapping of high Z elements on orbits in the Earth's magnetic field may lead to a sufficient enhancement of the intensity of particle flux to make it possible to detect these elements by satellite experiments. Calculations are presented that predict the behavior of trapped particles as a function of the predicted flux and energy distribution of high Z elements incident on the Earth's magnetic field. Techniques are suggested for the detection of such particles. In addition, the possibility of production of transuranium elements in the recently discovered pulsars are discussed.

One of the most interesting developments in nuclear physics during the past decade has been the prediction by nuclear stability theorists of the possible existence of relatively long lived nuclei with atomic number around 114-- isotopes of the so-called superheavy elements. This possibility has prompted physicists and chemists to institute a search for them in (a) naturally occurring materials such as ores and meteorites and (b) as a small fraction of the cosmic ray flux. Pioneering balloon experiments by Price and Fowler (1-5) have resulted in the detection of one or two particles which may have $Z > 92$. The purpose of the present paper is to explore the possibility that transuranium and superheavy elements may remain trapped by the earth's geomagnetic field for appreciable periods of time. It is shown that if detectors are flown aboard satellites in the regions in which such a "holdup" of particles occurs the counting rates may be greatly in excess of those possible in balloon experiments. The orbits where elements of various energies would be trapped are described and a detection scheme is suggested.

It has been shown (6) that perturbations in the cosmic ray flux at the earth could be produced by pulsars. The theory that nuclear events taking place in pulsars could lead to the creation and acceleration of superheavy nuclei has also been discussed in recent papers (7,8). If these theories are correct, it is possible that nuclei with half lives as

small as 10^4 years, originating from pulsars, could be detected and the sensitivity of detection increased by searching with satellite borne detectors in regions of the geomagnetic field calculated on the basis of particle trajectories.

"SUPERHEAVY" ELEMENTS

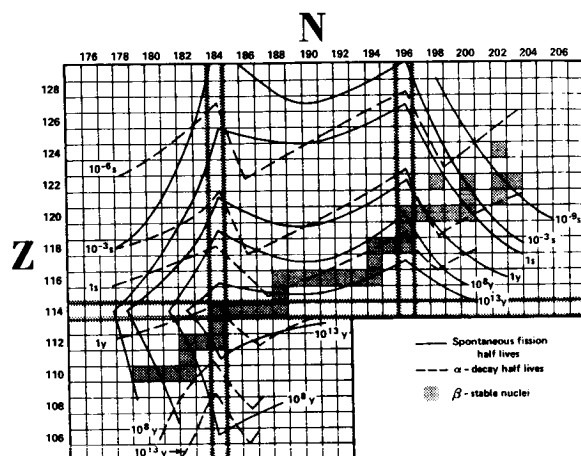
The presently popular unified theory of nuclear stability combines features of the charged liquid drop model of the nucleus (used for many years to explain nuclear fission in both qualitative and quantitative terms) and the shell model of the nucleus, by which the nuclear potential of individual nucleons can be computed--the nucleons being arranged in quantum orbitals similar to the more familiar electron orbitals which determine atomic structure (9). Out of this theory has come a set of predictions, based in part on known nuclear properties of isotopes, which indicates that the decline in nuclear stability with increasing atomic number that is observed with the known chemical elements will be reversed if so-called "superheavy" elements could be created. The hypothetical superheavy elements constitute a region of exceptional nuclear stability believed by most theorists to center around atomic number 114. The atomic number 114 is computed to be a "magic number" or closed shell of protons. Additional nuclear stability in this region is afforded by a predicted closed neutron shell of 184 neutrons.

Consequently, the isotope with atomic number 114, neutron number 184, and derived mass number of 298 is doubly magic and should be remarkably stable. "Stability" here really means resistance to decay by spontaneous fission, and this mode of decay would be overriding in the absence of any stabilizing influence of the closed nucleon shells. In the case of the half life of the isotope $^{298}_{114}$, for example, its half life for spontaneous fission is predicted to be 10^{20} years, whereas empirical extrapolations of the spontaneous fission half lives of known trans-uranium isotopes would indicate that the spontaneous fission half life of $^{298}_{114}$ should be vanishingly small. If exceptional stability toward spontaneous fission is accepted, at least in principle, then other possible modes of decay must be considered for any given isotope to determine which is controlling. The results of such a study are shown in Figure 1, which is the work of C. F. Tsang at the University of California, Berkeley (10). From the figure it can be seen that the isotope with $Z=114$ and $N=184$ is stable against beta particle decay, but has a half life of only about one year for alpha particle emission. From an overall viewpoint, the isotope with $Z=110$ and $N=184$ is optimally stable, having a net half life of the order of 10^8 years when all modes of decay are taken into consideration.

THE OCCURRENCE OF SUPERHEAVY ELEMENTS IN NATURE

Such theoretical considerations have prompted several experimental physicists and chemists to institute a search for trace quantities of superheavy isotopes in naturally occurring materials. They have followed one or the other of two lines of reasoning. First, if one assumes that superheavy elements can be created by the same nuclear processes that led to the known elements (primarily the r-process in Type I supernovae for heavy elements),

then these elements should be present in exceedingly small concentrations in minerals which contain large proportions of elements chemically homologous to the superheavy element being sought, provided that the half life of the superheavy isotope or isotopes is of the order of 10^8 years--long enough to have survived the period of time that has elapsed since the creation of the elements of the earth. The search based on this hypothesis has been intensive but inconclusive (11).



Half Life Contours for Region of Exceptional Nuclear Stability

SUPERHEAVY ELEMENTS IN COSMIC RAYS

The second possibility is that superheavy isotopes are being formed in cosmic nuclear processes of more recent vintage than the events which led to the creation of the solar system, and that cosmic rays should contain a small proportion of such isotopes. This line of thinking has been further stimulated by the remarkable work of P. B. Price, R. L. Fleischer, and R. M. Walker, and associates at the General Electric Research and Development Center and Washington University (Price is now at the University of California, Berkeley) and

P. H. Fowler and his group at the University of Bristol, England (1-5). These groups have collaborated on several occasions to measure the charge distribution of heavy cosmic rays in a series of balloon flights over the United States. The American group collects cosmic ray tracks in stacks of plastic sheets, while the British workers use nuclear emulsion sheets for recording the tracks. Since the two media are arranged contiguously in the balloon flights, a heavy cosmic ray track recorded in one medium typically will also be recorded in the other, permitting correlation of the responses observed. As shown in Figure 2, the correlation of cosmic ray atomic numbers (Z) as measured in plastic sheets, versus the values obtained for the same cosmic rays in nuclear emulsion is very good, except for one event with $Z > 100$ --the most interesting event (4,5). Usually only tracks which penetrate all sheets were accepted for measurement. Measurement of the tracks produced in the sheets, has resulted in the histogram shown in Figure 3, taken from reference (5) representing the results of two balloon flights in 1968. The one event shown at $Z=104$ (in emulsion) is assigned a charge of 92 in Lexan and 93 in cellulose triacetate. It was registered in all three materials (the only track so to be found and examined) with essentially a uniform response and its velocity was determined to be at least 0.92c. Price et al postulate that this particle was more likely a long-lived isotope with $96 \leq Z \leq 98$ rather than with $110 \leq Z \leq 115$. That is, it probably was an isotope like ^{247}Cm or ^{244}Pu rather than a superheavy isotope. The best value assigned is $Z \approx 96$, $\beta \approx 0.95$, but higher and lower values cannot be ruled out completely.

RELATIVE ABUNDANCE OF VERY HEAVY COSMIC RAYS

According to Price et al (5), of 10^{10} cosmic ray primary particles that passed through two stacks of plastic sheets and nuclear emulsion sheets, about 3×10^6 particles were in the iron group ($24 \leq Z \leq 28$). After scanning 75% of the area of these sheets, three particles with $Z > 83$ were found, indicating that less

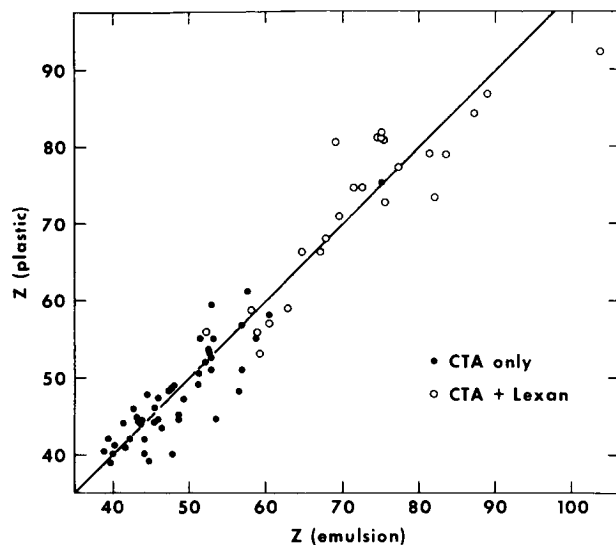


FIGURE 2

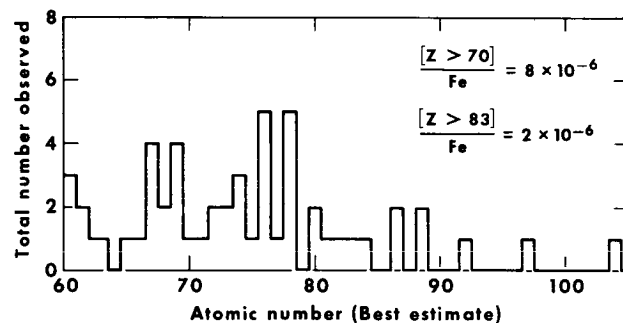


FIGURE 3

than one cosmic ray in 10^9 primaries has a charge greater than 83. Summing the data from the experiments, Price et al state that $\frac{[Z > 83]}{\text{Fe}} = 2 \times 10^{-6}$, which would indicate that cosmic rays with $Z > 83$ relative to the total primary flux would be $\frac{(2 \times 10^{-6}) (3 \times 10^6)}{10^{10}} = 6 \times 10^{-10}$, also equivalent to less than one heavy particle in 10^9 primaries. Also useful is the histogram reproduced from reference (5) as Figure 4, which indicates that the

absolute flux of cosmic rays with $Z > 80$ is about 0.03 particle/m² day steradian at the top of the atmosphere.

From the data deduced above, it is apparent that efforts to determine whether the super-heavy elements ($110 \leq Z \leq 126$) can be found in cosmic rays are greatly limited by using balloons to expose plastic sheets and nuclear emulsions to extremely small fluxes of heavy particles. The balloons cannot stay aloft for more than a day or two and their load-lifting capacity is restricted.

The following discussion will illuminate some of the favorable aspects a satellite experiment would have in regards to the detection of a large number of particles.

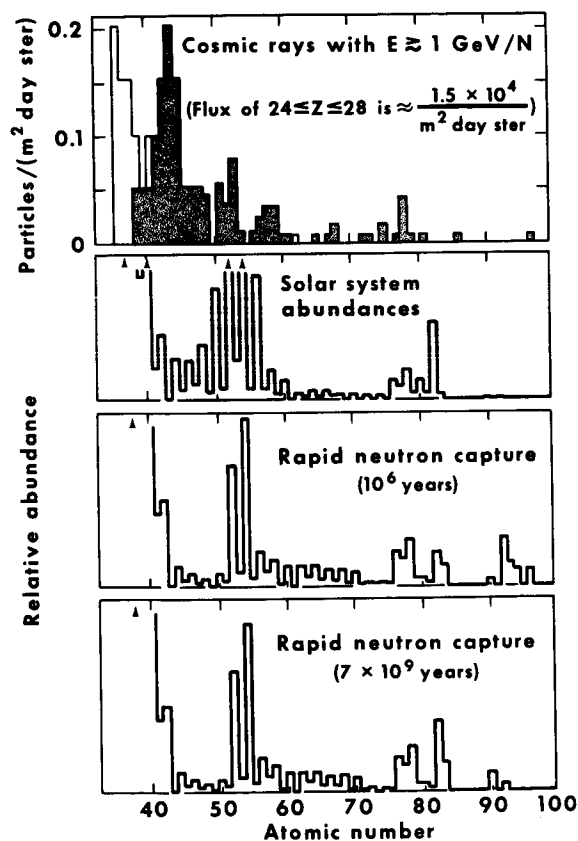


FIGURE 4

GEOMAGNETIC TRAPPING

The computation of cosmic ray trajectories in the Earth's geomagnetic field has reached a high degree of sophistication. Early work by Stoermer (12), Lemaître and Vallarta (13) and others showed that the cosmic ray intensities, measured on earth, should be a function of

location with respect to the Earth's magnetic poles. These theoretical calculations show that, depending on location, there is a "cutoff rigidity" (momentum per unit charge) which is the lowest rigidity a cosmic ray can possess and still arrive at a specific point on the earth's surface. In 1961, Gail and Lifshitz (14) proposed the temporary capture of primary cosmic ray particles on unstable periodic orbits in a dipole, as a mechanism contributing to the formation of Earth's radiation belts. The major sources of the radiation belts are now believed to be the trapping and subsequent acceleration of solar wind particles and the decay products from cosmic ray albedo neutrons. Other minor sources are solar cosmic rays (either by direct injection or via albedo neutrons) or a neutral component in the solar wind. Thus, the Gail and Lifshitz (14) paper was not the explanation of the radiation belts. However, their mathematical analysis of the unstable periodic orbits in a dipole field was correct. More recently an extensive amount of work has been done by Smart, Shea and Gail (15,16) in computation of charged particle cutoff rigidities and special orbits in which the earth's internal magnetic field is represented by a Gaussian expansion with IGRF coefficients (17) up to $n=8$, and the external field due to currents in the magnetopause and neutral sheet by the Williams and Mead expression (18). A class of orbits is found in these calculations in which particles of rather high rigidity, (1-10 BV) can remain in the vicinity of the earth for periods of time long compared to the bounce time between magnetic turning points. These orbits in which particles are held up for a large number of bounce periods lie typically 1 to 2 degrees below the normal cutoff latitude for particles of a given rigidity. One of these trajectories has been calculated for us by Shea and Smart, and a portion of the trajectory is illustrated in figure 5 for a superheavy element with $Z=114$, $A=298$, and an energy of 0.1 BeV per nucleon (rigidity of 1.16 BV). This particular trajectory resulted in the trapping of the particle for approximately 30 seconds, which was time for

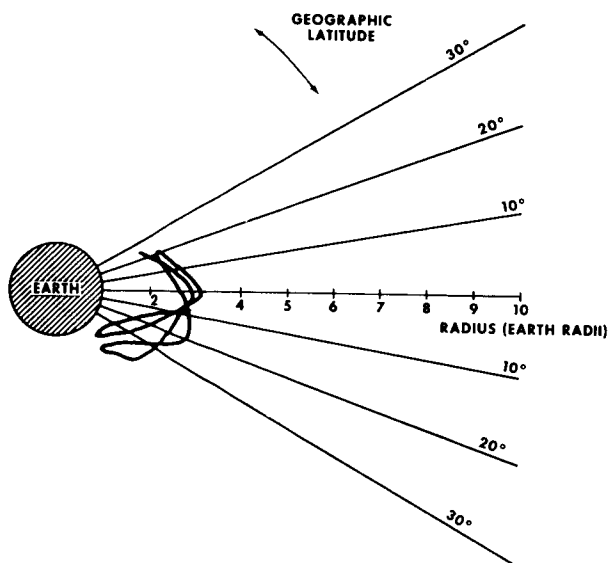


FIG. 5

four complete longitudinal orbits around the earth and 90 bounces between the latitudinal turning points. The motion occurred at a distance of approximately 3 earth radii.

While these calculations were performed with computational techniques, a general picture of the behavior of isotopes of various energies and charge to mass ratios can be obtained by approximating the earth's field as a dipole. (For high rigidity particles the earth's magnetopause and neutral sheet have little effect on the orbits). The location of the orbital regions in which isotopes may be trapped is a function of both energy/nucleon and Z/A . However, the possible range of values of energy is much greater than the range for Z/A and thus one might first look for iron say, then look for the heavier isotopes. The best orbital region for observing superheavy elements will be a function of the best estimate of the particle energy spectrum. This effect is illustrated in figure 6 where, for turning points at $\lambda = 30^\circ$, the location of the trapping regions are illustrated as a function of energy

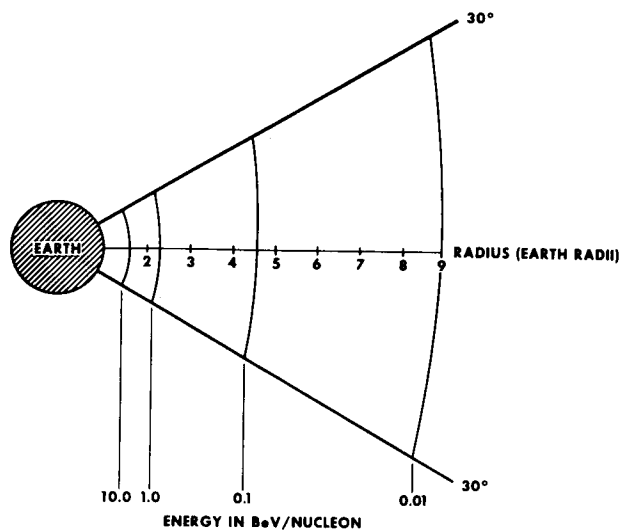


FIG. 6

per nucleon for a superheavy isotope with $Z=114$, $A=298$. For comparison, the trapping regions for iron with $Z=26$, $A=56$,

a proton, and a superheavy element is illustrated in figure 7 for 500 MeV/nucleon particles.

Thus, we have shown, with a detailed calculation of a trajectory, that for a superheavy element, orbital regions exist in which the particle can be temporarily captured by the earth's geomagnetic field. The generalization of this effect to other isotopes has also been presented. Satellite detectors located in these regions in which particles can be temporarily trapped would be expected to provide a detection capability superior to that of balloon experiments. The degree of increase in superheavy element detection capability is a function of four factors:

- (1) The possibility of an interaction between the superheavy elements and atmospheric atoms is reduced.

- (2) An omnidirectional sensor located in one of these regions will detect a flux several times greater than that of an unidirectional sensor. See for example, Ray (19). This enhancement in detection capability is consistent with the Liouville Theorem.
- (3) These orbits, which are sometimes referred to as asymptotic to the periodic orbit, are very close to actual "trapping" regions, in which particles can remain until a scattering event removes them. Thus, if adiabaticity is violated during injection, or if an interaction occurs with any of the fluctuating electromagnetic fields in these regions, a trapped population could be formed. The detailed mechanism by which particles are trapped by the earth's geomagnetic field is still only partially understood. Thus, the enhancement of intensity of high rigidity isotopes expected in these regions would have, as an upper limit, the ratio of intensity of high rigidity protons in the radiation belts to the incoming flux of high rigidity radiation. This ratio is about 10^4 . The decay products of albedo neutrons undoubtedly account for a significant percentage of high energy (> 100 MeV/Nucleon) trapped radiation; therefore, this ratio may be too large by a factor of ten or more. The relative fluxes of various components of the earth's radiation environment are shown in figure 8.
- (4) Finally, the increased observation time possible with a satellite would make it possible to observe a larger integrated flux.

The instrumentation of a satellite to detect superheavy elements and to provide for transmission of such data by telemetry to an earth station does not exist at the present time although in reference (20), a thorough description is given of cosmic ray telescopes which have been flown aboard satellites to detect particles with charges ranging up to those in the vicinity of iron. These telescopes could be used to study possible trapping regions for cosmic ray nuclei. One possibility for

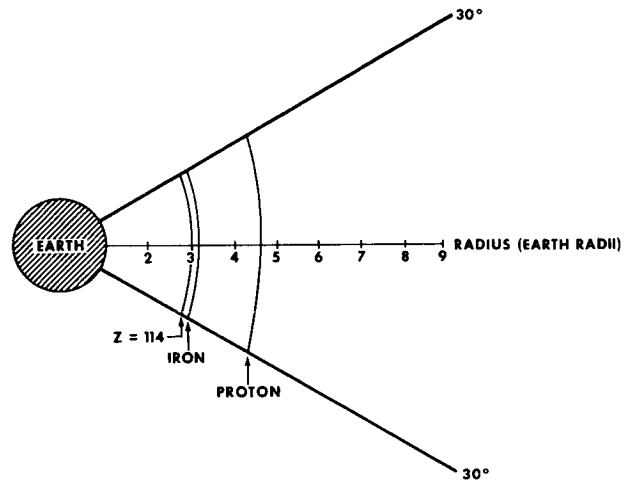


FIG. 7

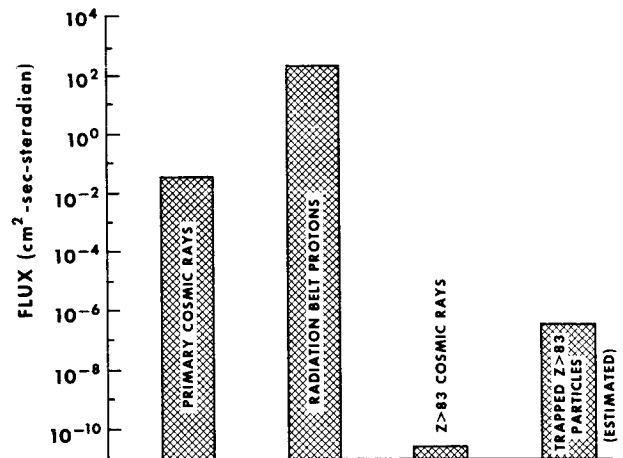


FIG. 8

superheavy element detection would be to place the detector sheets in orbit with a recoverable satellite. The plastic detectors can be made insensitive to elements in the iron group or lower and thus screen out the very intense light components of the earth's radiation environment.

PULSAR SOURCES

Pulsars have been suggested as sources for at least some of the cosmic rays (7,8). These pulsars are thought to be "neutron stars" which consist primarily of a neutron "superfluid" at a density of 10^{15} gms/cm³. The outer layers are not well understood and could consist of either an exotic crystalline solid or a gas. Thus, the mechanism for heavy cosmic ray formation could be related to some evaporative process. One such process was suggested in 1949 by M. G. Mayer and E. Teller with their "polynutron" theory (21). If superheavy elements are formed on or near the surface of a pulsar, then the rapid rotation characteristic of these objects, through interactions with intense magnetic fields believed to be connected to the object, could provide sufficient energy to both accelerate and eject the elements from the star. P. B. Price, et al, have dismissed the pulsars as possible sources of superheavy elements because the solid portion of the crust of a neutron star is thought to consist mainly of iron. Such a conclusion may be premature as there is no direct experimental evidence on the composition of the neutron star. The only well known facts are that they are very dense, rapidly rotating objects which are releasing large amounts of energy.

An analysis of the possible contribution to the general cosmic ray flux by discrete pulsar sources has been carried out by Lingenfelter (6). His calculations included considerations of the age of the pulsars, their distance from the earth and diffusion in the interstellar medium. He finds that the pulsar PSR 1929+10, which is only 0.14 KPC from earth and is estimated to be only 6×10^4 years old, could be influencing cosmic ray flux at the present time.

Other, older pulsars are also found to be a possible influence on the cosmic ray flux.

CONCLUSIONS

We have attempted to show that it would be advantageous to search for temporarily trapped isotopes with satellite experiments. The particular case of superheavy elements is discussed and trajectories are shown to exist

on which these particles would spend a considerable period of time. The regions defined by the trajectories have characteristics that could result in a significant enhancement of the hypothesized superheavy element component of cosmic rays, compared to that detectable in balloon experiments. While the percentage of superheavy elements in the geomagnetic trapping regions may be very small, the ability to build a detector that is insensitive to charges in the iron region or lower makes it

possible to search for these elements without interference by the much more intense proton or alpha particle fluxes. The degree of increase in counting rate possible (compared to a balloon experiment) is estimated to be between a factor of 10^3 and 10^4 .

A satellite search for superheavy elements is made even more attractive when one considers the possibility of discrete sources, such as the pulsars. If the lifetime of superheavy elements is less by a large factor than the estimated maximum half-life of 10^8 years, then only nearby sources could contribute to an observable flux. Furthermore, the flux from discrete sources would then approach the earth's magnetic cavity from a specific direction and trajectories followed by these particles will be a function of the orientation and detailed structure of the geomagnetic field with respect to the source. As shown in reference (6), sources as young as 10^4 years could be influencing the cosmic ray flux at the earth and thus, a satellite--borne experiment might permit detection of superheavy elements with lifetimes on the order of 10^4 years.

This idea is based, at the present time, on a number of plausibility arguments. Much more detailed calculations would be necessary before planning an actual experiment, especially since the cost of recovering a scientific payload from an orbit of several earth radii would be large.

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